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The Frank-Hertz experiment

Introduction:
The Frank-Hertz experiment shows the structure of the atomic orbital: electrons revolve round the nucleus in discrete orbits with binding energies for the outer electrons in scales near 1eV. Furthermore this experiment should teach the students to get used to measuring instruments and to practice their adjustment.

First experiment:
Task:
1. After assembling the wiring of the arrangement properly, mercury, which is kept in a tube surrounded by an oven, is heated to a temperature of about 180°C.
2. By adjusting the heating to a sufficient level, a current of electrons exits the cathode and the diagram appears on the screen.
3. The decelerating voltage is measured to $U_G = 1{,}28V$.
4. The drawing of the diagram to be found in our record book.
5. Our measured voltage differences between two maxima result in the mean value: $\overline{U}_B = 4{,}9V$, the standard deviation: $s = 0{,}332V$ and the standard deviation of the mean value to the confidence level 68,3%: $\Delta\overline{U}_{B,S} = s\frac{t}{\sqrt{n}} = s \cdot 0{,}51 = 0{,}17V$.

   In addition there is the deviation of the measuring devices. We found out a tolerance of $\Delta\overline{U}_{B,M} = 0{,}5V$.

   Quadratical addition leads to: $\Delta\overline{U}_B = \sqrt{\left(\Delta\overline{U}_{B,S}\right)^2 + \left(\Delta\overline{U}_{B,M}\right)^2} = 0{,}53V$

   ⇨ $U_B = (4{,}9 \pm 0{,}53)V$

   The wavelength of the emitted photons is: $\lambda_{Hg} = 2{,}5 \cdot 10^{-7}m \pm 0{,}27 \cdot 10^{-7}m$ with $\overline{\lambda}_{Hg} = \frac{h \cdot c}{e \cdot \overline{U}_B} = 2{,}5 \cdot 10^{-7}m$ and $\Delta\overline{\lambda}_{Hg} = \frac{\Delta\overline{U}_B}{\overline{U}_B} \cdot \overline{\lambda}_{Hg} = 0{,}27 \cdot 10^{-7}m$.

Second experiment:
Task:
1. We assemble the wiring of the arrangement properly.
2. By adjusting the heating to a sufficient level, a current of electrons exits the cathode and the diagram appears on the screen. To gain a good Frank-Hertz diagram with distinct extrema, you have to adjust the space-charge grid by varying its potential.
3. The decelerating voltage is measured to $U_G = 4{,}8V$.
4. The drawing of the diagram to be found in our record book.
5. Our measured voltage differences between two maxima result in the mean value: $\overline{U}_B = 19{,}7V$, the standard deviation: $s = 1{,}67V$ and the standard deviation of the mean value to the confidence level 68,3%: $\Delta\overline{U}_B = s\frac{t}{\sqrt{n}} = s \cdot 0{,}51 = 1{,}0V$.

   In addition there is the deviation of the measuring devices. We found out a tolerance of $\Delta\overline{U}_{B,M} = 0{,}5V$.

   Quadratical addition leads to: $\Delta\overline{U}_B = \sqrt{\left(\Delta\overline{U}_{B,S}\right)^2 + \left(\Delta\overline{U}_{B,M}\right)^2} = 1{,}1V$

   ⇨ $U_B = (19{,}7 \pm 1{,}1)V$

Questions:

a) Explain the terms *elastic collision* and *inelastic collisio*n.
For both, the elastic and the inelastic collision, the constancy of the impulse is valid. But for the elastic collision the energy is also constant. This means that the whole kinetic energy of both particles is the same before and after the collision. If the particles have different masses they move with another speed after the elastic collision. By an inelastic collision the energy is transferred - in this case an outer orbital electron is put to a higher level of energy.

b) Why is an electron at energies below 4.9 eV only able to perform elastic collisions?
According to the Bohr model electrons in outer orbitals have only discrete values of energy. The lowest possible binding energy for a Hg-electron is 4.9 eV, i.e. an electron with less than 4.9 eV cannot excite the outer Hg-electron because of the discrete energy levels of the atom. The result is an elastic collision.

c) Why is the energy an electron can transfer to an atom low in elastic collisions?
There is nearly no transportation of energy, because of the mass of a moving electron being so small relatively to the mass of a stationary atom. You can better understand it by looking at the impulses:

$$m_e \cdot v_{e,b} = m_e \cdot v_{e,e} + m_A \cdot v_{A,e}$$

$$v_{e,b} = v_{e,e} + \frac{m_A}{m_e} \cdot v_{A,e}$$

$$\left(v_{e,b} - v_{e,e}\right) \cdot \frac{m_e}{m_A} = v_{A,e}$$

m_e: mass of the electron
m_A: mass of the atom
$v_{e,b}$: speed of the electron at the beginning
$v_{e,e}$: speed of the electron at the end
$v_{A,e}$: speed of the atom at the end

(The speed of the atom at the beginning is supposed to be zero.)

$m_e << m_A$ ⇨ $v_{A,e}$ is very small ⇨ the energy of the atom is nearly not changing.

This can be compared with a collision of a table-tennis ball with a wall: the wall doesn't move, the ball is just reflected.

d) How does an atom excited by an inelastic collision dispose itself of the acquired energy?
The electron that was put to a higher level of energy returns to its original level. By doing this it emits a light quanta whose length is the difference of the value of energy the electron had before and the value of energy it has now. (Also see the equation (2) in the experiment guidance, page 1)

e) What is the difference between the excitation of an atom by electrons and by light quanta?
When there's an excitation of an atom by a light quanta, the whole energy of the light quanta is taken by the atom. That means the light quanta "disappears". An atom can only take discrete values of energy, so the light quanta must exactly have this value of energy, otherwise the light quanta can't be absorbed and there is no exchange of energy.
In spite of that it is possible that an electron, which has a little bit more energy that is needed, can excite an atom. The energy that can't be transferred to the atom is kept by the electron as kinetic energy.

f) Why is it necessary to apply a deceleration voltage between collector electrode and anode grid?
Without a deceleration voltage all free electrons would get to the collector electrode. But those electrons which just had a collision with an atom shouldn't get to the collector electrode. Otherwise the number of electrons which reach the collector electrode would only depend on the number of electrons that come from the cathode. So you would have no idea about what's happening in the tube.

g) Compare the functionality of a Franck-Hertz tube with that of a fluorescent lamp and try to understand this lamp with the help of the schematic sketch. Why are these lamps called fluorescent lamps? [cf. Bergmann-Schäfer, Lehrbuch der Experimentalphysik, vol. III (Optik)]
The principle function of a fluorescent lamp is the same. In a fluorescent lamp there's no need for a cathode heating, because the free electrons are created by collisions among the atoms of the gas. The gas in a fluorescent lamp is usually mercury (Hg). The light which is emitted by Hg is usually in the UV-spectrum, so you can't see it. Therefore you need a fluorescent film on the inner side of the tube which emits light that you can see. That's why this lamp is called a fluorescent lamp.

h) What is the difference to an x-ray tube?
In contrary to the Frank-Hertz tube there's a vacuum in the x-ray tube, because on their way from the cathode to the anode the electrons mustn't have any collisions with any atoms. The electrons are supposed to be very fast, in order to create high-energy quanta. The acceleration Voltage is much higher than that of a Frank-Hertz tube.